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Environmental Conditions Responsible for Solar Activity

Annual Technical Report
For the Period 01 Oct 91 through 01 Oct 92

Principal Investigator: Professor Peter A. Sturrock

Grant No.: F49620-92-J-0015

Program Manager: Dr. Henry R. Radoski

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CENTER FOR SPACE SCIENCE AND ASTROPHYSICS
STANFORD UNIVERSITY
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13. ABSTRACT (Maximum 200 words)
This report describes progress toward understanding the theoretical basis for solar activity. One of our key accomplishments has been the insight we have gained into the eruption of coronal magnetic structures. Roumeliotis, Sturrock and Antiochos have made numerical and analytic calculations which indicate that coronal magnetic fields being sheared by convective motions acting on their photospheric footpoints evolve smoothly until the shear surpasses a certain critical amount. After that, the coronal field exhibits very sensitive dependence on the photospheric boundary conditions, in the sense that small changes in the footpoint displacements produce huge changes in the height of the coronal field. We propose that this nonlinear behavior of sheared magnetic fields is the explanation for eruptive phenomena such as coronal mass ejections and solar flares. We are also developing several approaches for understanding coronal heating. In particular, Sturrock has proposed a model in which turbulent reconnection deep within the chromosphere produces local heating as well as a burst of magnetohydrodynamic waves that propagate upward to heat the corona. Roumeliotis is working on the theory that twisted flux loops in the corona undergo an internal resistive kink instability that unwinds the internal field and releases magnetic energy to heat the loop.

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1. Introduction

The goal of the Stanford group is to develop a broad theoretical understanding of solar activity. Some of the most important manifestations of solar activity include the transient heating of plasma within active regions, eruptive solar flares, and coronal mass ejections. During the past year, our theoretical efforts have been stimulated by the unprecedented images of the active corona taken by the Soft X-ray Telescope onboard the Yohkoh satellite. The observing instruments on Yohkoh have revealed two fundamental pieces of information about the solar corona that must be addressed in any theoretical program aimed at understanding the origins of solar activity. Firstly, Yohkoh observes continual eruptions of magnetic field and plasma within active region. Bubbles of plasma suddenly expand outward with velocities on the order of 30 km s^{-1}, sometimes attaining a new equilibrium configuration, and sometimes continuing to expand until they become part of the solar wind. Secondly, Yohkoh has shown more clearly than ever before that the hot X-ray emission from active regions is transient, with a time scale on the order of 20 minutes, and spatially organized into magnetic loops, with a length of approximately 50000 km and a width of only 5000 km. The newly emerging observational picture of the solar corona is providing valuable motivation and guidance for the development of theory.

2. The Eruption of Coronal Magnetic Fields

Essentially all of the activity observed in the Sun's corona is a consequence of the magnetic field that threads the solar atmosphere. Magnetic free energy is stored when photospheric shearing and twisting motions displace the footpoints of the coronal magnetic field. This basic scenario has been in circulation for decades, but the details of how magnetic free energy is built up and released in the corona have remained a puzzle. One of our key accomplishments in the past year is an improved understanding of the eruption of coronal magnetic fields.

The most impressive solar eruption is the coronal mass ejection (CME). Before it erupts, a CME has the appearance of a huge dome of plasma which expands over several days. Then suddenly, the CME is unleashed, flinging plasma and magnetic field out to great distances from the Sun. As we noted above, Yohkoh has shown that much smaller eruptions also occur continually within active regions. It appears likely that the eruption of coronal magnetic fields is a basic process. Thus, for example, the small scale eruptions within active regions must often be accompanied by the formation of plasmoid; these escaping plasmoids may be the source for replenishment of the solar wind. Also, the process of eruption can drive different magnetic structures together, thereby creating intense electric current sheets between these systems and providing the initial "spark" that triggers the rapid reconnection and energy release of solar flares.

Roumeliotis, Sturrock and Antiochos (1993) have developed a numerical code to follow the evolution of a force-free coronal magnetic field as increasing footpoint displacements are applied at the photosphere. For our first calculations, we have assumed that an initially potential dipole magnetic field is buried within the Sun. Motions that are antisymmetric about the equator are then applied at the photosphere. We adopt a spherical polar coordinate system in which the z-axis coincides with the rotation axis of the Sun. The angular positions of the magnetic footpoints at the solar surface are evolved according to

$$\phi_{footpoint}(\theta, t) = \phi_{max}(t)\, F(\theta) \quad ,$$

where $F(\theta)$ is a fixed profile which vanishes at the equator and the poles, and which has a maximum amplitude of unity. A key feature of our calculation is that a change of variables is made which allows the outer numerical boundary to be placed at 1000 solar radii. This is very significant, as the sheared magnetic field expands dramatically. Previous calculations have placed the outer numerical boundary at 10 or 20 solar radii, thereby missing key aspects of the dynamics of this highly nonlinear system. The results of our calculation are summarized in the sequence of frames shown in Figure 1. These frames show the projection of the magnetic flux surfaces from the upper hemisphere onto the r-θ plane. As the footpoint displacements at the solar surface are progressively increased, the coronal magnetic field expands outwards. But it does not expand uniformly. This can be seen by tracking the height of a specific field line, as shown in Figure 2. The height increases steadily until the maximum shear angle, ϕ_{max}, approaches 130°. Past this amount of shear, the height of the field line increases dramatically for tiny changes in the footpoint positions. We propose that this qualitative change in the behavior of the sheared, expanding magnetic field corresponds to the onset of eruption in coronal magnetic structures.

Sturrock (1993) has developed an asymptotic theory that captures much of the qualitative behavior of our numerical model. A new graduate student, Slava Glukov, has joined our group and will be focusing on force-free field problems. In particular, he will study how the results described above generalize to different geometries and initial conditions, and he will incorporate the effects of finite gas pressure into the numerical computations.

$\phi_{max} = 0$

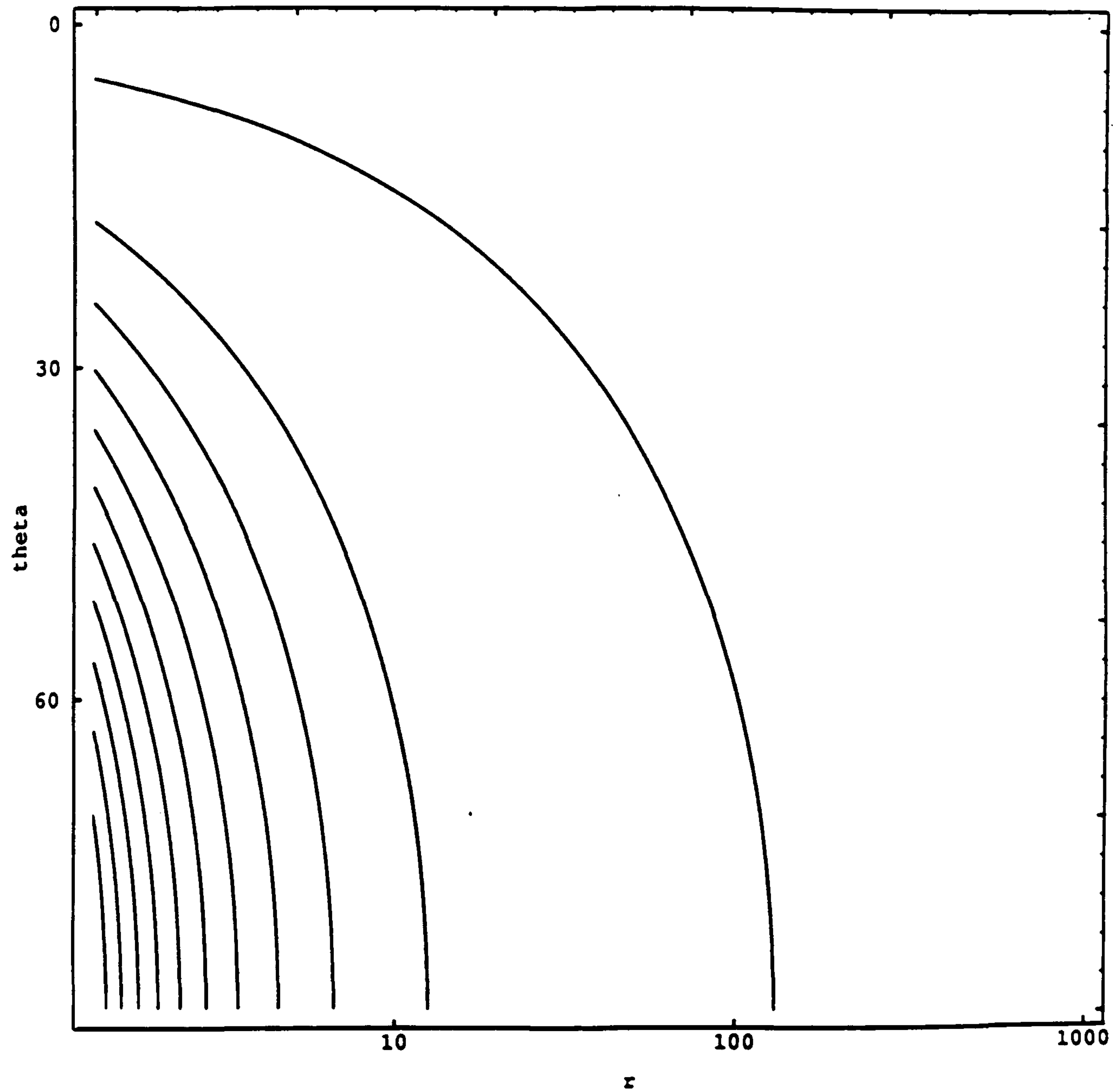

Figure 1 (a).

$\phi_{max} = 45°$

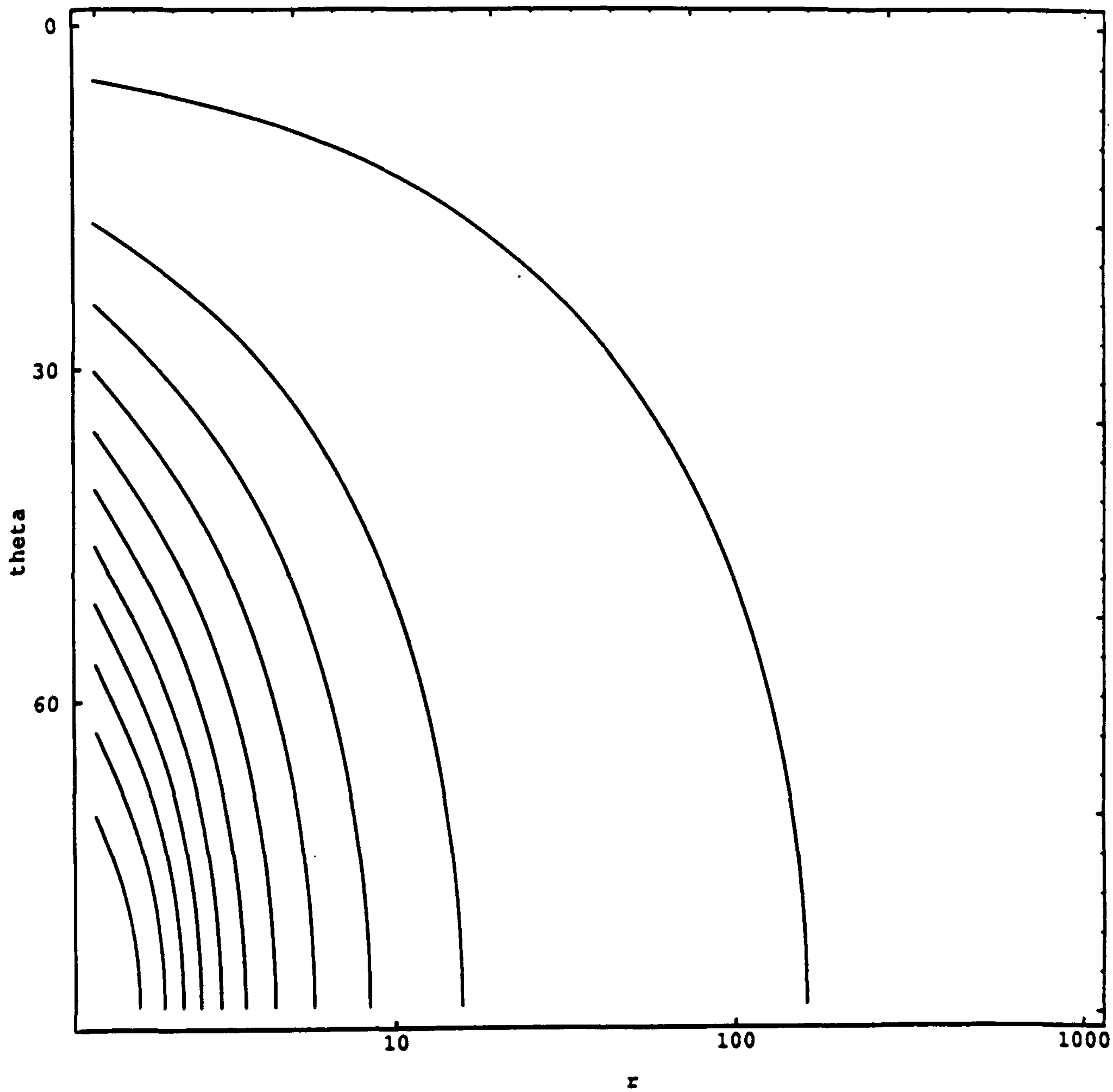

Figure 1 (b).

$\phi_{max} = 90^o$

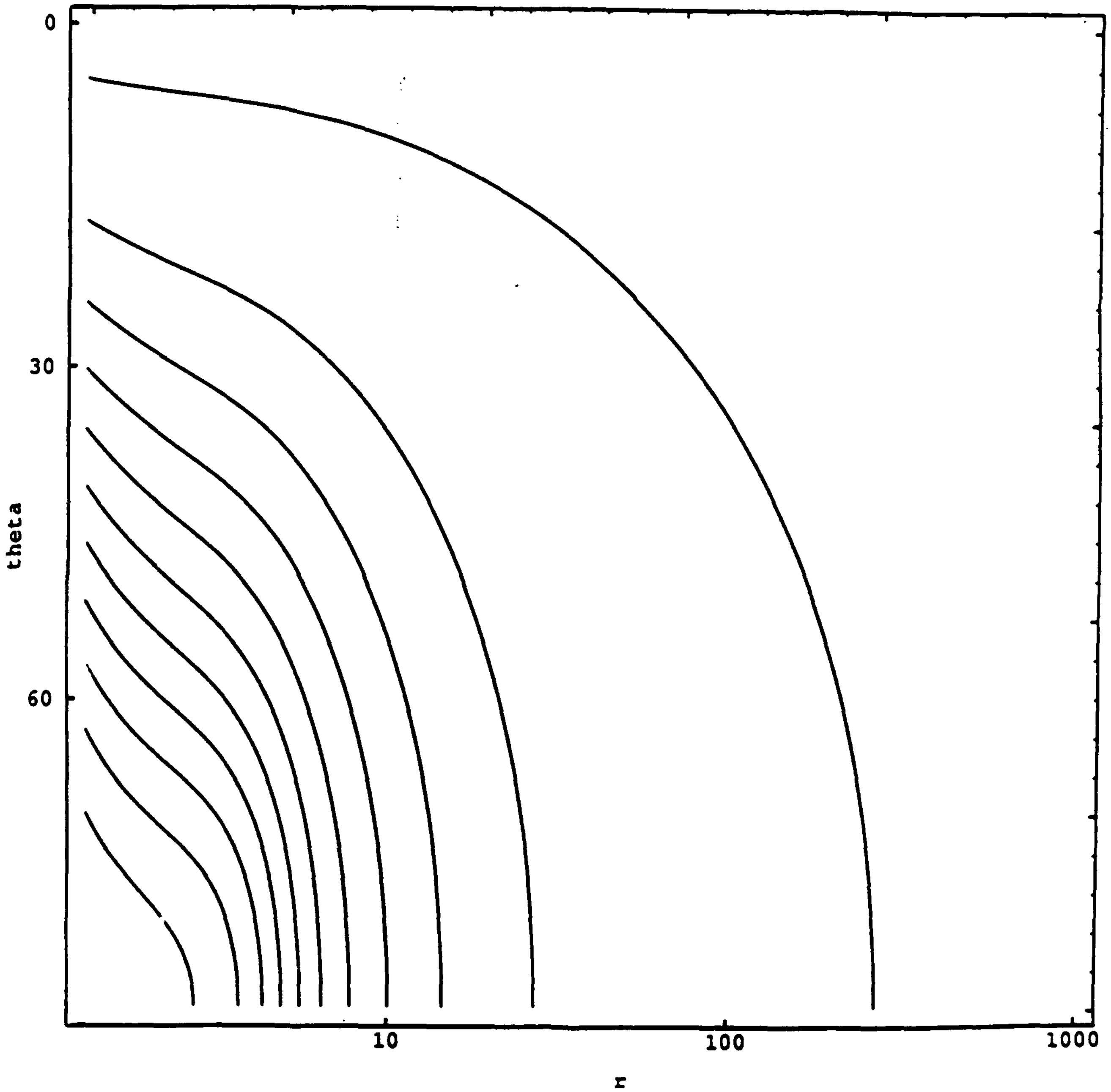

Figure 1 (c).

$\phi_{max} = 135°$

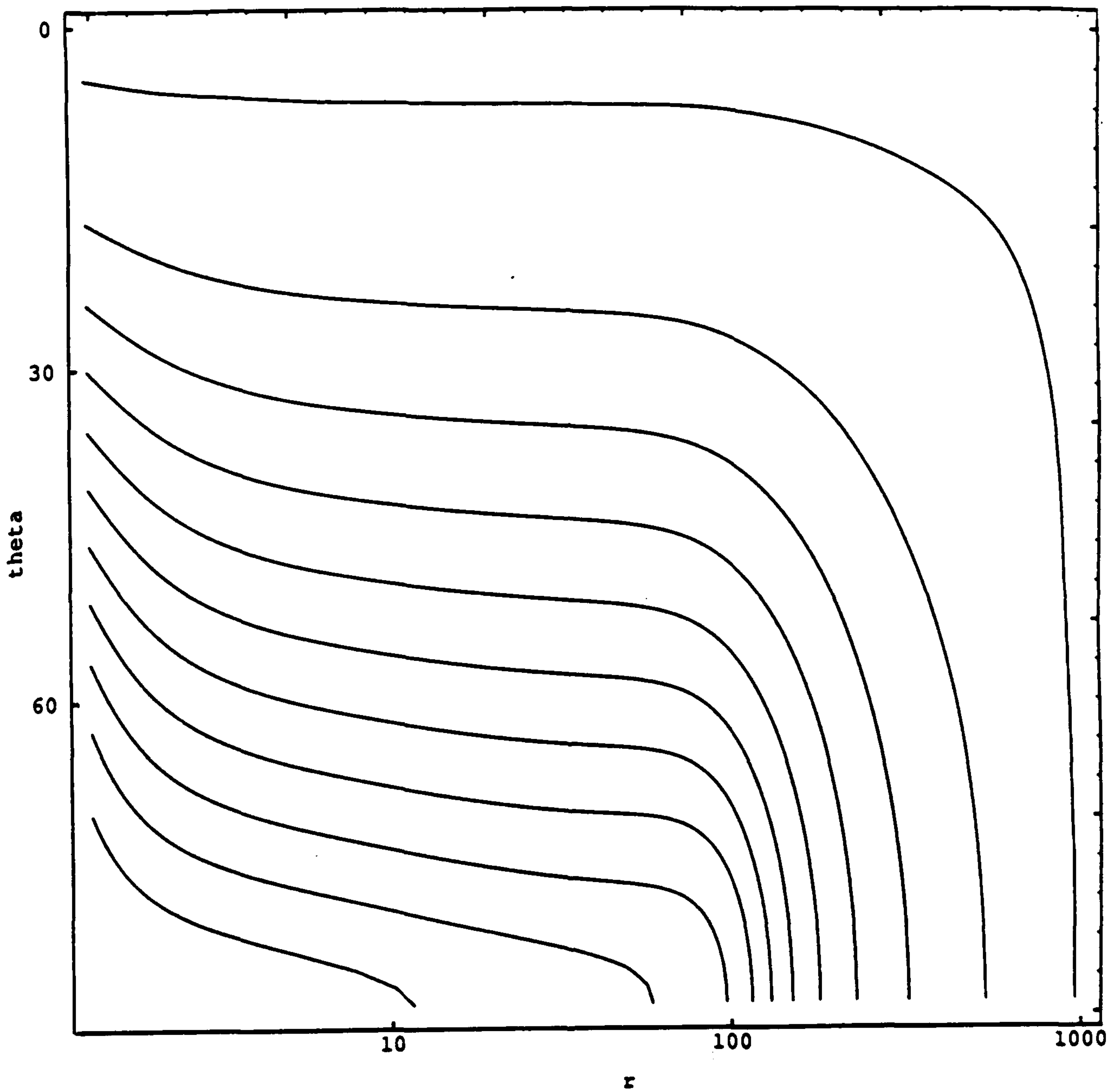

Figure 1 (d).

$\phi_{max} = 180°$

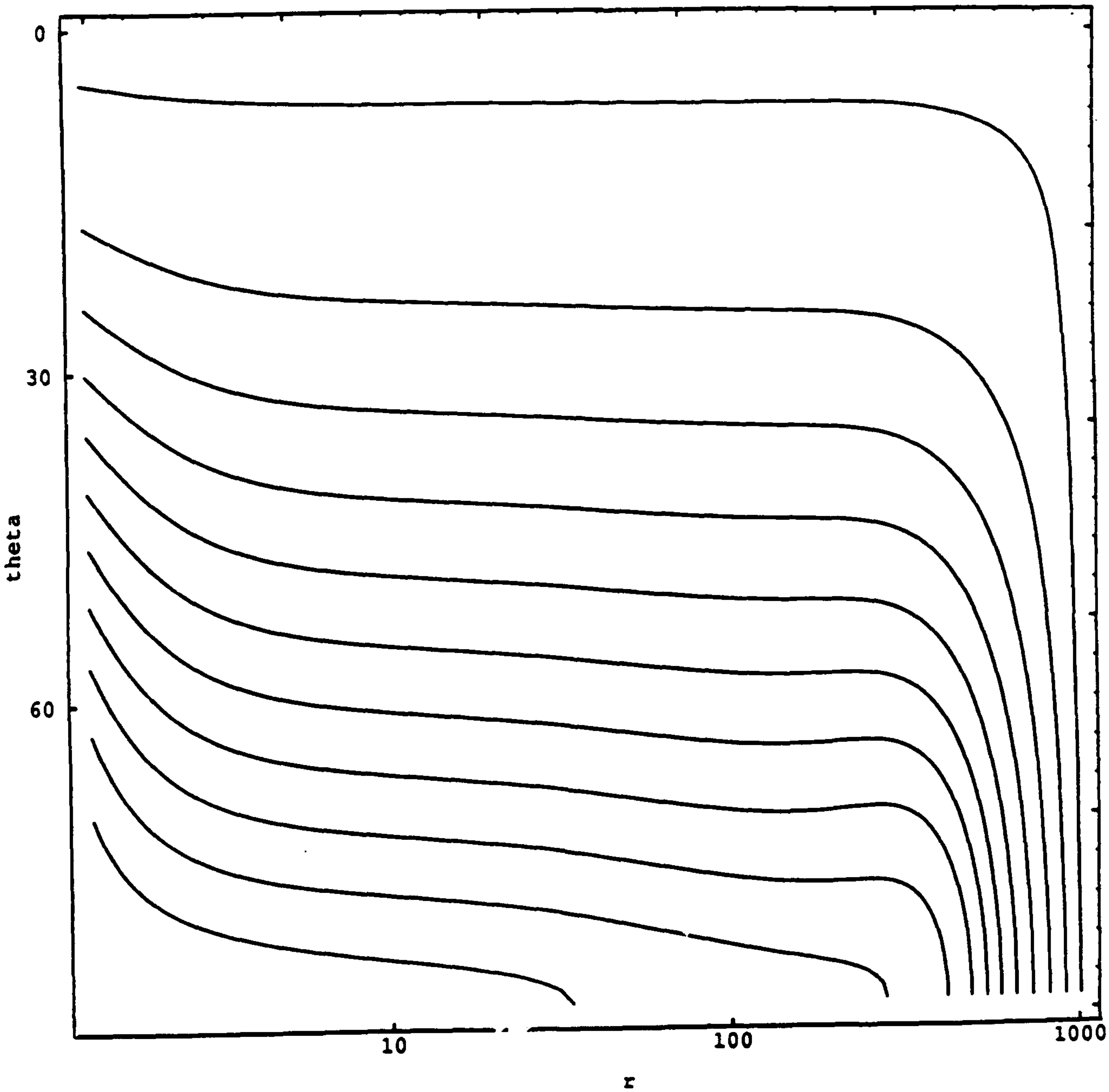

Figure 1 (e).

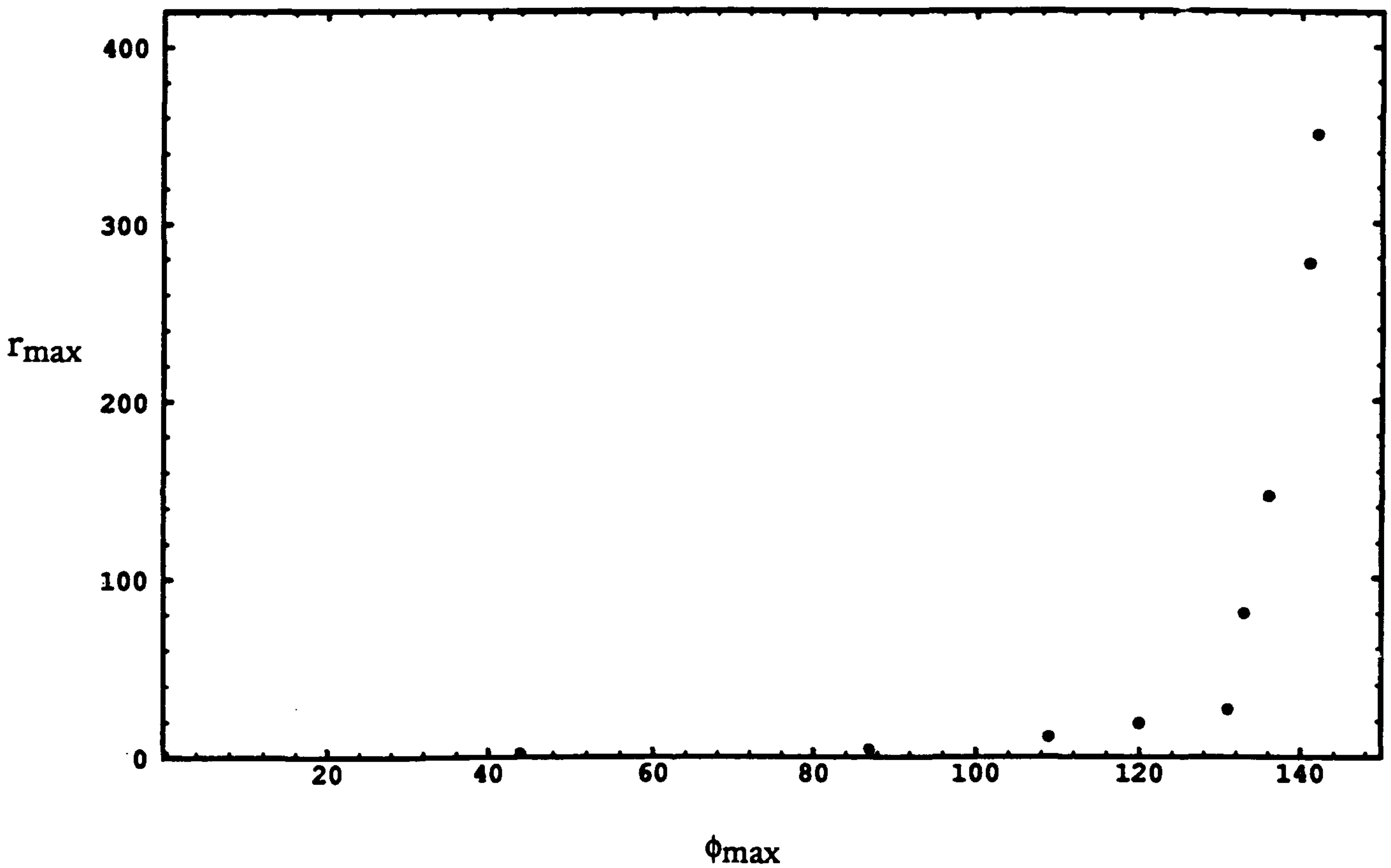

Figure 2.

3. Mechanisms of Coronal Heating

The basic test for whether one understands coronal heating is to construct a model solar atmosphere and compare the properties of the model with observations. The magnetically closed regions of the outer solar atmosphere are usually studied with one-dimensional hydrodynamic loop models. These closed regions include the bright loops that are readily visible in EUV and X-ray images, as well as the fainter, more diffuse plasma that surrounds the Sun. Klimchuk (1992) has reviewed the current state of knowledge concerning static and dynamic loop models and their observational signatures. He summarizes the basic theoretical properties of static, steady-state and time-dependent models, and compares these properties with observations. He concludes that none of the currently proposed coronal heating mechanisms can adequately explain the observational data.

Sturrock is developing an alternative theory for coronal heating, based on the notion that there must be a close relationship between coronal and chromospheric heating. One reason for suggesting such a relationship is that the injection of hot plasma into a coronal loop is invariably accompanied by chromospheric microflares at the base of the loop. Sturrock's scenario for coronal heating begins with the magnetic flux tubes that extend from the photosphere through the chromosphere and into the corona being twisted by photospheric vortex motions. As the amount of twist is progressively increased, a resistive tearing instability is triggered in the deep chromosphere where the electrical resistivity is largest. This resistive instability quickly destroys the laminar, sheared magnetic field in the chromosphere, replacing it with a turbulent sea of magnetic islands. The shredding of the chromospheric magnetic field produces a burst of heating that is the origin of microflares. At the same time, the turbulent magnetic eddies generate short period magnetohydrodynamic (MHD) waves that propagate into the overlying atmosphere where they dissipate to heat the corona.

A crucial question in Sturrock's unified explanation for coronal and chromospheric heating is how the short period (< 100 s) MHD waves are damped in the corona. Lisa Porter, a graduate student, has made significant progress toward answering this question. Porter has derived a very general sixth order dispersion relation for linear MHD waves in a homogeneous background with a uniform magnetic field. Both compressive ion viscosity and electron thermal conduction are included as dissipation mechanisms, and no assumption concerning the smallness of the damping is introduced. Her work represents a significant generalization of the earlier studies in the literature. The dispersion relation has solutions representing damped fast mode waves. So far, Porter's calculations indicate that fast mode waves can provide adequate energy to heat the quiet corona, but there remains a difficulty in meeting the energy requirements for active regions, where the magnetic field strength is an order of magnitude larger than in the quiet corona. Porter is currently extending her work by considering the propagation and dissipation of waves within inhomogeneous coronal structures. As revealed by Yohkoh, the basic building blocks of active regions are coronal loops in which the plasma is hotter and denser than the surrounding atmosphere. We believe that the reflection and interaction of MHD waves within the highly inhomogeneous environment of coronal loops will lead to more efficient dissipation of these waves.

Roumeliotis is also using the observational fact that active regions are spatially structured into loops as the basis for a coronal heating theory. The soft X-ray images from Yohkoh show that active regions are made up of long thin loops, but they also reveal that these loops have a uniform diameter along their length. This is an unexpected finding, since one would naturally assume that the loops would bulge out in the manner expected of a dipole magnetic field. One possible explanation for the constant thickness of active region loops is that they are twisted by vortical motions at the photosphere. This in turn suggests a possible heating mechanism. In the theory of controlled fusion, it is well known that a twisted magnetic loop is susceptible to the m=1 resistive kink instability. In this instability, the core of the twisted loop is spontaneously pushed to one side. A thin reconnecting layer is formed, and the instability proceeds until the core has completely reconnected. An intermediate stage in the evolution is shown in Figure 3. The time taken to completely reconnect the core has been roughly estimated as

$$\tau \sim \tau_R^{1/3}\, \tau_A^{2/3}$$

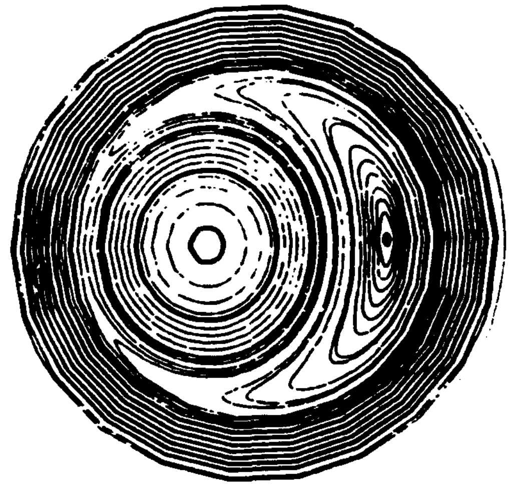

Figure 3.

where τ_R is the resistive diffusion time of the loop and τ_A is the Alfvén transit time across the loop. Roumeliotis has noted that in an active region loop, one typically estimates

$$\tau_A \approx 0.1 \text{ s}$$

$$\tau_R \approx 10^{12} \text{ s}$$

which implies that the time scale of the resistive kink instability is about 30 minutes. This is precisely the time scale that is observed for impulsively heated loops by Yohkoh. Roumeliotis is developing a detailed theoretical model for the resistive kink instability under conditions appropriate to the solar atmosphere. In particular, twisted magnetic loops must be anchored to the photosphere at both ends and confined by the magnetic pressure of other magnetic loops rather than the solid walls of a laboratory containment device.

3. Related Topics

Recently, it was discovered by Rieger et al. (Nature, 312, p 623, 1984) that solar flare activity exhibits a periodicity of about 154 days. This discovery was a great surprise at the time. Since then, not only has this periodicity been found in the activity data of earlier times, but also other related periodicities have been discovered. Bai and Sturrock (1991) have recently found intriguing relationships among the periodicities in solar activity that may provide a clue to their origin. In addition to the 154 day periodicity, periodicities of 51, 78, 84, 103 and 129 days have been found from the analysis of various solar activity data for cycles 19 through 22. Because these periods, except for 84 days, are integral multiples of about 25.5 days, Bai and Sturrock have proposed that there is a "clock" within the Sun with a fundamental period of 25.5 days.

In order to quantify the properties of this "clock", Bai and Sturrock (1993) have studied the distribution of major flares in coordinate systems rotating about arbitrary axes with arbitrary periods in the 24.5 to 26.5 range for solar cycles 19 through 22. In this study, Bai and Sturrock have found evidence for two exciters rotating with a period of 25.50 days about an axis tilted by 40 degrees with respect to the ecliptic normal, toward the position of the Earth on December 4. The rotation of these exciters is interpreted as the mechanism that modulates the solar activity.

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